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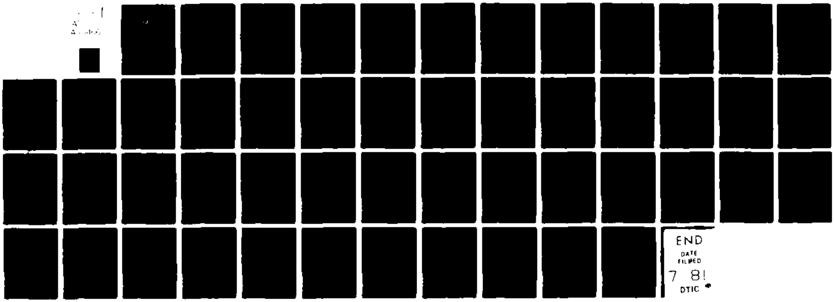

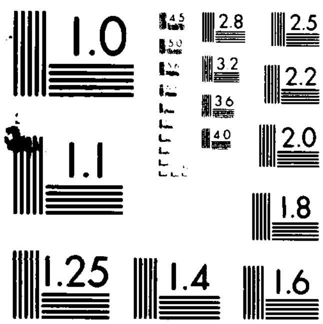

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Abstract

Human operators are increasingly being called upon to function as monitors of automatic systems. System monitors, as opposed to active controllers, do not necessarily experience lower workload levels during task performance. In fact, prior research has suggested that workload demands may not be reduced but rather shifted to a functionally separate processing "pool" according to a structure specific view of human attention. Sternberg's additive factors method may provide a useful workload assessment technique for localizing the information processing demands of task performance. The present study couples a primary failure detection task with a secondary Sternberg task which employed a perceptual and response load manipulation. The results demonstrated a significant overlap of processing resources for the failure detection task and the Sternberg perceptual condition. For the response load condition, there was no evidence of shared resources between the two tasks. These results have significant implications for task configuration and workload assessment research.

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THE STRUCTURE OF PROCESSING RESOURCE
DEMANDS IN MONITORING AUTOMATIC SYSTEMS

BY

JOHN MICALIZZI

B.S., United States Air Force Academy, 1979

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Arts in Psychology
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INTRODUCTION

The role of the human operator has undergone dramatic revision in recent years with the continued encroachment of automation into the human domain of man/machine systems. The human operator's function has steadily evolved from that of a manual controller of dynamic systems to the role of a monitor and supervisor of automated systems. Unfortunately, this evolution, in many cases, has not been accompanied by a corresponding development of sensitive research methods to investigate the qualitatively different demands which are placed on human monitors. Automation will never eliminate operator effort and its introduction into the task situation may not necessarily serve to reduce the load experienced by human monitors. The purpose of this study is to further explore the information processing demands of monitoring automatic systems. First, however, the research literature on failure detection and workload assessment will be reviewed to provide an introduction to theoretical and methodological considerations.

Human Monitoring and Failure Detection

The task of monitoring system dynamics may encompass several behavioral objectives including failure detection. However, the actual objectives of human monitors will be difficult to specify in complex systems where many possible objectives exist (Curry, 1979). The more demanding supervisory function may also entail such activities as failure detection, identification, and corrective action on the part of the human operator whose responsibility it is to monitor and control large panels of instrumentation (Rasmussen, 1968). Detecting system changes or failures, whether in a supervisory or purely monitoring capacity is, therefore, a

critical aspect of modern human operator behavior.

In the loop vs. out of the loop. During the past two decades, failure detection researchers have considered the issue of whether humans are better detectors of system failures when they are in the loop exercising active control over the system or out of the loop as passive monitors. Proponents for active human control argue that increased vigilance and faster adaptation (e.g. taking manual control of failed automatic system) are logical grounds for keeping the human in the loop. On the other hand, out-of-the-loop advocates consider the increased capacity for processing information from other sources and the possibility of designing systems to perform functions beyond the capabilities of human operators as valid reasons for retaining the human operator as a passive monitor.

The results reported in the experimental literature on this issue have been inconclusive in establishing any clear cut superiority of one mode over the other. Curry and Eprath (1976) report that most previous investigations into the adaptability of the human operator have concentrated on sudden and usually severe step changes in control element dynamics. However, even those experimental investigations which have utilized more subtle changes in system dynamics as "failures" have not resolved the issue.

Wickens and Kessel (1979a) compared the effects of two modes of participation on failure detection performance. In the manual (MA) mode, subjects were required to control the system in tracking a two-dimensional pursuit display. Operator input was perturbed by Gaussian noise which was analogous to the buffeting effects of wind gusts on an aircraft. In the autopilot (AU) mode, the human controller was replaced by an autopilot which simulated human control input, reducing the operator's role to that of a

system monitor. Operators in both modes were required to detect failures which were relatively small step increases in system order. The results indicated that the MA mode displayed superior failure detection performance, both in terms of accuracy and latency.

On the other hand, Eprath and Curry (1977) investigated the effects of gust disturbances and the pilot's participation mode on failure detection performance during a simulated, low visibility landing approach. They reported that participation mode had a significant impact on human detection of subtle, slow failures in the lateral and pitch axes. A failure in the monitored axis was detected significantly faster than in the manually controlled axis.

The incongruity of the above results reveals the necessity to specify under what conditions monitors are better failure detectors than controllers. Curry and Eprath (1976), drawing upon the work of Young (1969), have developed a model to predict whether monitors or active controllers will be better failure detectors under certain conditions. According to model predictions, monitors will provide faster detection latencies "if the control task requires considerable attention to steering displays, if there is slow adaptation on the part of the controller, or if there is a low signal to noise ratio in the control residual" (Curry & Eprath, 1976, p. 143). This model is consistent with results reported by previous investigators. This ability to predict whether system monitors or controllers will provide superior performance represents a significant step in understanding human failure detection abilities.

<u>Monitoring behavior in automatic systems</u>. In the past, automatic systems were developed primarily with the intent of reducing operator

workload. By automating a task which was previously performed by a human operator, system designers and engineers speculated that a considerable amount of time and effort could be released and channeled into other, more important areas of task performance. The operator in early automated systems still retained the ability to intervene manually in the case of system failures. Under these circumstances, considerations of active control versus passive monitoring still constituted relevant design alternatives.

However, automation has recently moved toward extending the capabilities of the human operator so that manual intervention would cease to be a feasible option. Automated tasks are progressively exceeding the abilities of human control. In the case of autopilot systems, automation was initially introduced with the objective of easing pilot workload (Johannsen, Pfendler & Stein, 1976). Nevertheless, subsequent applications to supersonic and, eventually, hypersonic aircraft would involve operational tasks which the human monitor is quite unprepared to assume in the event of a failure. The introduction of automation, in this case, would not necessarily ease the load upon the human operator. But rather, the use of automatic systems would enhance the operational effectiveness of the man/machine system by changing rather than reducing the human contribution (Edwards, 1976). It is imperative that experimental research continues to be aimed at investigating the workload demands of the human monitoring process.

Quantitative models of human performance are particularly useful methods for describing and predicting human monitoring behavior. The construction of mathematical models partly depends on concise formulation of

hypotheses about the human operator. Curry and Gai (1976) have suggested several hypotheses for the human monitor based on manual control theory (Clement, Mcruer, and Klein, 1971) which form the fundamental basis for many modelling approaches:

> 1. To accomplish system monitoring functions such as monitoring the state of the system and its various subsystems (including displays and failure detection systems), the operator uses a variety of models about the system and its performance based on his past experience.
> 2. To be satisfactory, monitoring systems comprising both animate and inanimate components must share certain of the qualitative dynamic features of "good" failure detection systems of the solely inanimate nature. As the adaptive means to accomplish this end, the observer must make up for any deficiency of the information displayed by appropriate adjustment of his dynamic information processing.
> 3. There is a cost to this adjustment--in workload induced stress, concentration of observer faculties, and in reduced potential for coping with the unexpected. This cost can also be traded for the cost of automatic monitoring systems. In making this trade-off, one may allocate part of the task to the human and part to the automatic failure detection system. (p. 148)

Based on the above hypotheses, Curry and Gai (1976) have described a model of human detection of changes in mean of a random process. Their particular model includes two stages: A linear estimator and a decision mechanism. The validity of this model was tested in both tne laboratory and in a more realistic setting involving automatic landing systems (Gai and Curry, 1976). In both situations, good agreement was found between predictions and experimental data.

Attempts at modelling the human failure detection process have continually focused on normative predictions of optimal operator behavior (Smallwood, 1967; Sheridan, 1970; Kleinman & Curry, 1977). However, recent research has indicated that there may be a significant discrepancy between predicted and actual sampling behavior of human monitors (Kvalseth, 1979) which may prompt alternative conceptualizations of visual processing as suboptimal behavior (Rouse, 1976).

Internal models. At the very center of virtually every attempt to more precisely model human behavior is the concept of the internal model. Veldhuyzen and Stassen (1976) observe that all forms of human behavior require some internal representation of the system being observed or controlled. The operator continually updates and compares his internal model to the actual system he is monitoring or controlling until the observed difference exceeds some subjective criterion and a "failure" is reported.

The internal model has proved to be of great utility in formulating quantitative theories of human monitoring performance. Smallwood's (1967) model provided a mathematical description of the updating of operator information by an internal model of the environment. Sheridan's (1976) generalized expected value approach to a model of supervisory control utilizes an internal model to predict the new process state resulting from any given action and initial process state. A utility function then specifies the worth of this change in state at the cost of that action. The optimal estimator of Curry and Gai (1976) is simply a Kalman filter based on the subject's internal model of the observed process. It is assumed that this filter reaches steady state after several observations and the human observer uses any error at the filter as an input to the decision mechanism. And finally, Rouse (1973) reported that subjects use mental models to predict future states from present observed states for discrete linear dynamic systems.

However, predictions based on the internal model concept are not always accurate (Veldhuyzen and Stassen, 1976) since:

1. The structure of the internal model may differ from the structure of the system to be controlled or monitored.

2. The internal model parameters may differ from the parameters of the system to be monitored or controlled.
3. System information can only be perceived with restricted accuracy.
4. Disturbances are often not known exactly. (p. 110)

Given these nonlinear components of human behavior, the internal model construct is a useful but limited approach for predicting monitoring/controlling performance.

Investigations should also be directed at describing the development of an individual operator's internal model based on task demands and requirements. Jagacinski and Miller (1978) suggest that Bayesian decision theory can be viewed as an attempt to formalize and externalize a decision maker's internal model. However, Tversky and Kahneman (1974) caution that people tend to use nonoptimal, stereotypic models of probabilistic processes in estimating the likelihood of events.

Jagacinski and Miller's (1978) research effort utilized a behavioral approach which could provide evidence for the use of veridical or nonveridical models of controlled processes. By providing the operator with a simple task which allowed easy identification of operator failures to adequately characterize the response of the plant, this methodology permitted measurement of the internal model which could be communicated to the performer. Their results revealed the use of nonveridical models and indicated orderly changes in the internal model with practice. This technique, however, severely restricted the degrees of freedom in the human operator's response so that his ability to predict the time course of the dynamic system he is controlling could be more directly examined. Several critical assumptions involving methodological considerations may also limit the generality of these results. In addition, this derived conception of an individual operator's internal model does not define the specific,

underlying behavioral processes involved.

The internal model concept has been applied to the control of large ships (Veldhuyzen and Stassen, 1977), as well as monitoring a dynamic system to detect failures (Wickens and Kessel, 1979a). The information demands which result from the development and utilization of such internal models will provide a number of theoretical and applied problems for workload assessment research.

Workload Assessment and the Concept of Processing Resources

Workload assessment research represents a variety of concepts, models and methodologies which attempt to quantify the demand placed on an operator's limited processing abilities as he performs a particular task. System designers are especially interested in obtaining such a workload index to characterize the loading tendencies of a particular system. On the other hand, psychologists view workload assessment research as a means to explore the information processing abilities involved in many aspects of human behavior. The specific orientation adopted will strongly influence the concepts and techniques which will eventually be used. Wierwille and Williges (1978) provide an excellent survey of current workload methodologies utilized in both the theoretical and applied areas of aviation.

Workload research has continually suffered from the inability of measuring techniques to adequately distinguish between mental and physical workload demands. The physiological and psychological state of the individual are often confounded in many workload indexes. This limitation, however, has not seriously obstructed the progress of engineering psychologists in conceptualizing, modeling and measuring the mental effort

which may be involved in such psychological constructs as internal models, processing stages and attentional channels. Moray (1979) has compiled a series of papers whose common objective is to develop and clarify the theoretical and practical implications of mental workload.

The prevailing notion of human performance as a compromise between the information processing capabilities of an operator and the obvious storage limitations of his memory has been supported in part by the theories and models of human attention (Keele, 1973). From Broadbent's filter model (Broadbent, 1957), to Treisman's attenuation model (Treisman, 1964), to Norman's late selection model (Norman, 1968), the concept of selective attention has been developed in an effort to account for the processing limitations of human performance. Attention is itself a very broad area of psychological research, and workload occupies a particular niche in attempting to quantify the attentional demands inherent in a particular task situation. The costs associated with dual task performance, for example, have been described by attentional concepts and measured by workload assessment techniques in order to provide a sound theoretical basis for the hypothetical construct of "processing resources" (Wickens, 1979a). While structural theorists (e.g. Keele, 1973; Kerr, 1975) prefer to view processing resources as related to the discrete competition of tasks for specific processing mechanisms, proponents of capacity theories (e.g. Kahneman, 1973; Moray, 1967) emphasize the flexible nature of processing resources which permits allocation in response to task demands.

The structure specific resource model (Kantowitz and Knight, 1976; Wickens, 1980) represents a compromise between the structural and capacity views of human attention. The notion of a number of separate processing

reservoirs (as opposed to an undifferentiated pool) is consistent with many results reported in the dual task literature. Wickens (1980) has drawn upon the results of many dual task studies in order to develop a useful framework for determining the functional composition of these attentional resource reservoirs. His efforts have led to several promising candidates for resource definition including: stages of processing (perceptual--central processing--response), modalities of input (visual vs. auditory) and output (vocal vs. manual) and hemispheres of processing (verbal vs. spatial)(see Figure 1). This multiple reservoir view envisions task interference as a function of processing pool overlap.

Task interaction has been utilized as a common technique for assessing workload demands. If a capacity model of processing resources is adopted, then workload may be conceptualized as the proportion of total resources demanded by a particular task. The higher the workload, the less "residual capacity" is left available for performing any concurrent task. The secondary task technique exploits this relationship by requiring the subject to perform two concurrent tasks with explicit instructions to maintain a consistently high level of performance on one of the tasks. In order to assess the workload demands of the emphasized, or primary task, a secondary, or loading task is imposed as a measure of the residual capacity. Secondary task performance under dual task requirements is then compared with performance of the secondary task alone. This performance difference is taken as an index of primary task workload (Ogden, Levine, & Eisner, 1979). Assessment of relative workload levels for two pieces of equipment may also be accomplished by examining the fluctuations in performance of the secondary task. Large decrements in secondary task performance are

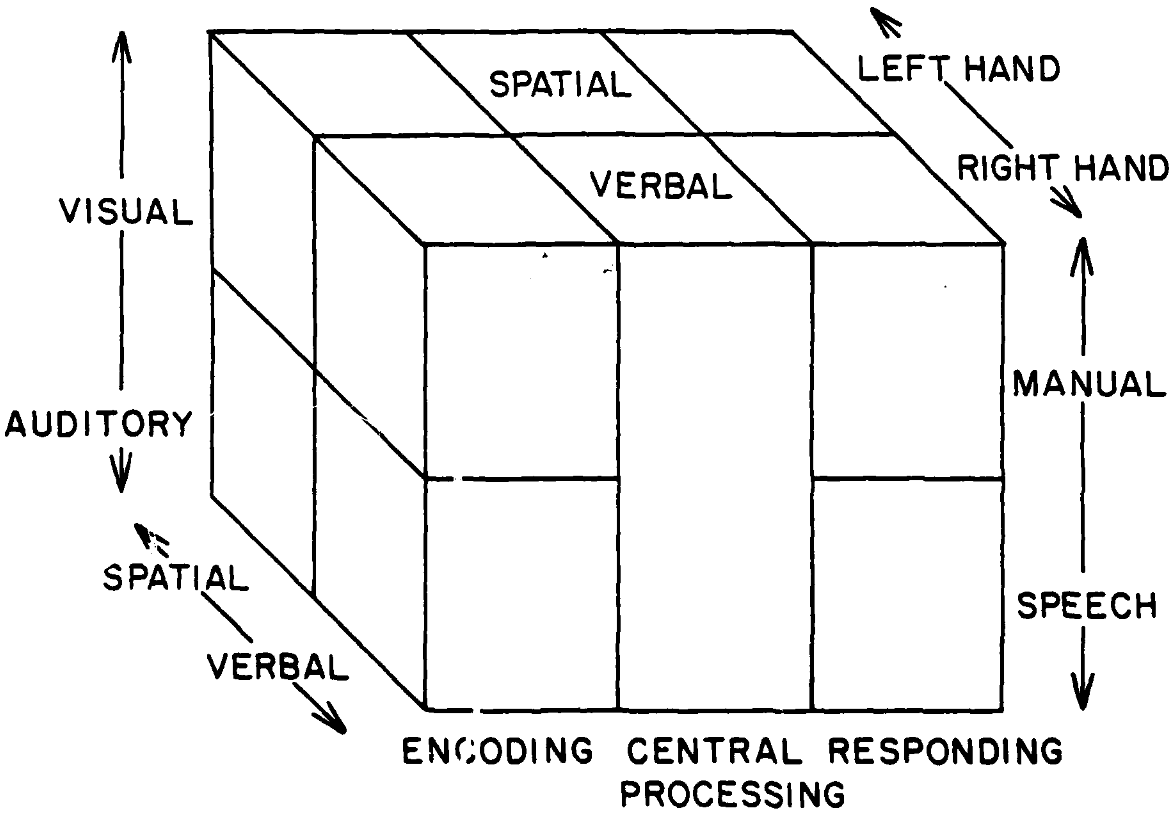

Figure 1. The structure of processing resources.

associated with high workload levels.

The usefulness of the secondary task methodology, however, may be c[illegible]d when applied to a multiple resource view of human attention (Brown, 1978). Under this model, it is possible to grossly underestimate primary task workload if the secondary task probes the wrong resource pool (Kantowitz and Knight, 1976). A response loaded secondary task will not yield a useful index of primary task workload if the primary task loads the perceptual encoding reservoir. However, adopting a multidimensional view of workload can explain the failure of the secondary task to reflect variations in primary task workload as a mismatch between resource pools demanded by the two tasks.

Adhering to the multidimensionality of workload measurement, Wickens and Kessel (1979b) investigated the demands of failure detection in dynamic systems according to a stages of processing approach. Failure detection performance in both the MA and AU modes was compared to the performance of each task alone and when it is performed concurrently with either a critical tracking task (Jex, 1967) or a mental arithmetic-memory loading task. The results of dual task performance indicated that the critical tracking loading task disrupted MA failure detection but not AU, while the converse results were obtained for the mental arithmetic-memory loading task. Interpreting these results within the framework of a structure specific resource model of human attention, the AU mode can be said to share processing resources with the mental arithmetic-memory task. These common resources reside primarily in the perceptual/central processing reservoir. On the other hand, the MA mode and the critical tracking task displayed similar processing reservoir overlap which was centralized in the response

related pool. Automation of the control function in the AU mode, therefore, does not eliminate the demand for processing resources but rather shifts the demand to a functionally separate processing stage.

Prior research in the area of workload and human monitoring behavior has suggested that minimal processing resource demands are involved in monitoring discrete stimuli (Posner & Boies, 1971; Keele, 1973), as well as continuous signals (Levison & Tanner, 1971). However, the research reported by Wickens and Kessel (1979b), as well as the research of other investigators (Senders, 1964; Isreal, Wickens, Chesney & Donchin, 1980), indicates that considerable processing demands are associated with some types of monitoring tasks.

According to the preceding discussion, human monitoring behavior in a failure detection task demands processing resources which reside primarily in the perceptual/central processing reservoir. This view is based on a structure specific view of human attention which emphasizes a stages approach to human information processing. The concept of mental processing as a set of discrete and serial stages, each with a constant input and output, has been a useful and convenient framework for examining the structure of mental activity. Psychological research continues to be aimed at a more precise delineation of these mental stages and the corresponding processes which may account for certain accepted abilities of the human as an information processor.

Sternberg's Additive Factors Method

The reaction time interval. The most common means for establishing the existence and structure of mental events has been the reaction time interval. The reaction time interval is a widely used dependent measure

which is relatively easy to obtain. Pachella (1974) argues that time itself is directly meaningful and not arbitrarily related to some underlying construct. The events under study fill real time, and thus, real time is the variable of interest.

Two types of converging operations have attempted to describe the activity which takes place during the reaction time interval: the subtraction method and the additive factors method. The subtraction method (Eriksen, Pollack & Montague, 1970) isolates a particular processing stage by construcing two qualitatively different tasks, one of which is believed to contain all the mental activities of the first except for one stage of interest. The reaction time difference for the two tasks indicates the amount of time the "subtracted" stage adds to total processing time. This method assumes that the experimenter has prior knowledge as to the sequencing of mental events and that deletion of a stage does not affect the activity of other mental stages. On the other hand, the additive factors method decomposes the reaction time interval through manipulation of experimental factors. These factors influence particular processing stages and produce converging patterns of reaction time data for their identification.

Theoretical overview. The additive factors method is based on Sternberg's investigations into the scanning of human memory. The data from Sternberg's (1966) character comparison task provides evidence that human scanning is both serial and exhaustive. The results indicate a strong linear relationship between the number of items in memory and response latency suggesting the presence of a comparison process between test stimulus onset and response execution. Each additional item in memory adds

approximately 38ms to the response latency. The essentially equivalent slopes for positive and negative responses also implies exhaustive search in that every item in memory is scanned regardless if a match was made previously.

Sternberg's (1967) subsequent experiments on character recognition investigated the nature of test stimulus encoding. Two separate and independent operations seemed to be involved in the character recognition process: Stimulus encoding and stimulus comparison. The independence between these two mental operations demonstrates an instance of additivity of two effects on reaction time. The effects of set size (comparison duration) and stimulus quality (encoding duration) on mean reaction time are independent of their respective levels. Such additivity supports the theory of a sequence of stages, one stage influenced by stimulus quality and the other by set size (Sternberg, 1969b).

Sternberg's approach assumes that the reaction time interval is filled with a sequence of independent stages of processing. Total reaction time, then, is simply the sum of the individual stage durations. When an experimental manipulation (factor) affects reaction time for a particular information processing task, it changes the duration of one or more of the constituent stages of processing. If two experimental manipulations affect two different stages, they will produce additive effects on total reaction time (see Figure 2). However, if two experimental factors interact, so that the effect of one factor is dependent on the level of the other, they must affect some stage in common.

Sternberg (1969a) utilized his character comparison task embedded in a series of multifactor experiments to investigate the effects of stimulus

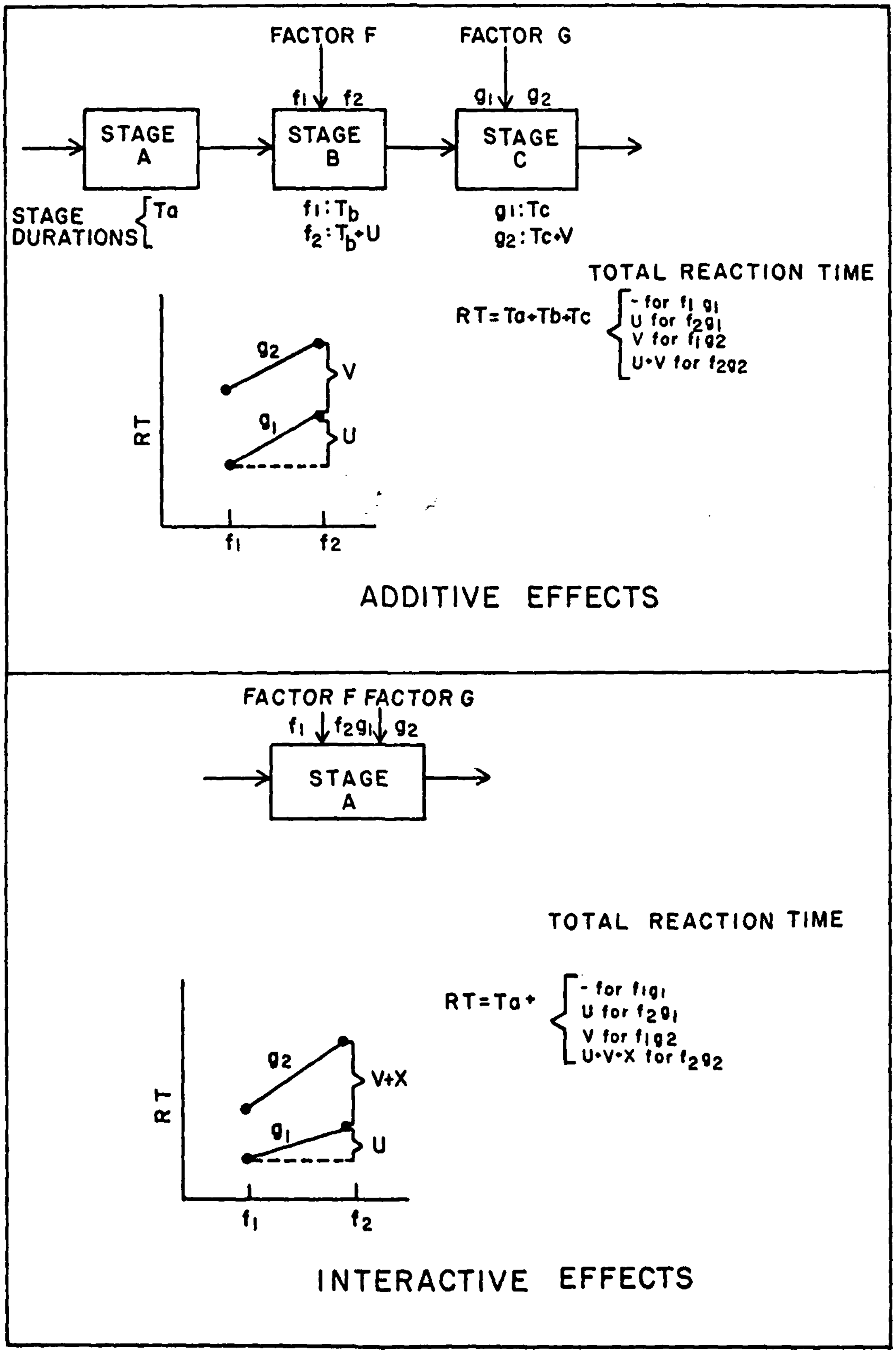

Figure 2. Sternberg's additive factors method.

quality, set size, response type and frequency of response type on reaction time. The data revealed a converging pattern of evidence which suggested that four stages of information processing were involved in the task: an encoding stage, a comparison stage, a response choice stage, and a response execution stage. It is important to note that the additive factors method does not provide a description of the stages or the sequence in which they occur. These labels result from corroborating evidence from other sources which also support a particular stage description or sequence.

The implication that these separate stages of processing draw from independent processing resources has been supported by dual task research. Several experiments have demonstrated that tasks which are perceptually loaded can be successfully timeshared with tasks that are primarily response loaded (Wickens, 1976; Wickens and Kessel, 1979b), although the functional separation between perceptual and central processing resources may not be as clearly defined (Shulman & Greenberg, 1971).

The additive factors logic has been utilized in a variety of experimental paradigms to further explore human information processing abilities. Sternberg's methodology has been employed in several dual task paradigms which have investigated the reaction time data associated with the study of the response decoding process (Briggs & Swanson, 1970), the localization of the divided attention effect (Briggs, Peters & Fisher, 1972), and the processing automaticity involved in search tasks (Logan, 1978), to name a few. These applications of the additive factors method are particularly useful within the context of workload assessment since the dual task data can provide an index of processing resource overlap between the manipulated reaction time task (inferred stage of processing) and the

concurrent task (Wickens, 1980).

Workload applications. The additive factors method has displayed an encouraging potential as a methodology for assessing primary task workload. Sternberg's character comparison task has been evaluated as a secondary measure of primary flying workload with promising results. Spicuzza, Pinkus, and O'Donnell (1974) utilized a fixed set procedure for both visual and auditory Sternberg stimuli coupled with a simulator flying task. In the visual condition, reaction time was plotted as a joint function of four levels of memory load and two levels of flight task difficulty. The effects of the set size manipulation of central processing load were additive with flight difficulty, showing an increase in the intercept across conditions. However, since the experiment did not include an encoding or response manipulation, the specific source of this demand could not be localized. In the auditory version, this increase in intercept was accompanied by a decrease in slope indicating some degree of processing overlap at high memory load levels. The Sternberg procedures appeared to yield consistent and interpretable data with predominantly linear trends, although important modifications are necessary for incorporation into the secondary task paradigm.

Crawford, Pearson and Hoffman (1978) have used the secondary Sternberg task as a measure of the reserve information processing capacity involved in two levels of flight control and four levels of multifunction switching. Slope and intercept variations were reported for the flight control conditions, while only intercept differences were observed for the multifunction keyboard conditions. These results suggest that flight control influences both input-output and central processing stages, while

anticipation of switching tasks affected the input-output stage only. These conclusions demonstrate that workload demands of multifunction switching are important considerations as the development and implementation of digital avionics information systems becomes increasingly common.

The additive factors method has been employed as an effective instrument for probing the dimensions of workload. The particular framework utilized has been derived from the research of Sternberg and others that difficulty manipulations in a memory search reaction time task affected stages of processing (perceptual encoding-central processing-response). Wickens, Derrick, Beringer, and Micalizzi (1980) imposed different levels of loading at each of these stages and coupled the Sternberg manipulations with a primary tracking task. Dual task reaction times suggested that tracking order interacts with perceptual/central processing load, but is additive with response load. Conclusions from this investigation indicated that the Sternberg manipulations can selectively delineate the locus of perceptual and central processing load from response load. Increasing the order of the tracking task seems to demand processing resources from primarily the perceptual/central processing reservoirs according to a stages of processing approach.

Similar variations of the Sternberg paradigm have coupled a monitoring task with the central processing manipulation to determine the locus of monitoring resource demands (Wickens & Micalizzi, 1980). Preliminary results are inconclusive in establishing the central processing reservoir as the source of monitoring processing load. The present investigation represents a follow-on to this monitoring study, requiring subjects to passively monitor a dynamic system and detect failures while performing a

concurrent Sternberg secondary task. The quantitative demands of failure detection will be varied across subjects by manipulating the cutoff frequency of the random noise function. The Sternberg manipulations will load the perceptual and response processing stages. Prior research has suggested that this failure detection task demands primarily perceptual processing resources and, thus, should interact with the perceptual Sternberg manipulation. These results would indicate that Sternberg's additive factors method could provide an effective tool for exploring the multidimensionality of workload demands.

METHOD

Subjects

Eight right handed male undergraduate students from the University of Illinois volunteered to participate in all experimental manipulations. All subjects had normal vision and were paid $2.50 per hour plus additional bonuses. The degree of right handedness was also evaluated for each subject to insure that the right hand was clearly dominant (Bryden, 1977).

Apparatus

Subjects were seated in a booth containing a 10 cm x 8 cm Hewlett Packard 1330a cathode ray tube (CRT), a hand control joystick with an index finger trigger operated with the left hand, and a spring-return pushbutton keyboard operated with the index and middle fingers of the right hand. The viewing distance from the subject's eyes to the CRT was approximately 86 cm, subtending a visual angle of 5 degrees. A Raytheon 704 sixteen bit digital computer with 24k memory was used to generate and control a single axis pursuit tracking display, present the Sternberg stimuli, and process subject responses on both tasks.

Tasks

Failure detection. This task is similar to the automatic mode (AU) of failure detection reported in Wickens and Kessel (1979a). In the present study, subjects were required to monitor a single axis pursuit tracking display which moved horizontally across the CRT. The target path was driven by a summation of two sinusoidal inputs while the autopilot transfer function consisted of a pure gain and 200 ms time delay to specify cursor

position on the basis of the error. A random noise disturbance was added to the output of the cursor. Thus the task might simulate a system following a semi-predictable path while compensating for disturbance gusts. System failures were simulated by a ten second linear ramp change in dynamics from a first order to a second order system. Subjects were instructed to press the joystick trigger with the left hand when they thought a failure had occurred. Four, five, or six failures occurred randomly during the two minute trial. A minimum of eight seconds had to elapse after a detection or miss before another failure could occur. As a manipulation of failure detection difficulty, the cutoff frequency of the random noise function was varied as an experimental factor (.32 Hz to .5 Hz) within subjects. The computer recorded hit latency and false alarms.

Sternberg task. The general Sternberg paradigm required subjects to recognize previously presented spatial information. Specifically, a spatially defined target, consisting of a random dot pattern, appeared on the CRT for ten seconds prior to each failure detection trial. Each presented pattern originated from an alphabetized set of twenty four separate and distinct dot patterns adopted from Wickens and Sandry (1980). After ten seconds, the dot pattern was removed and a clear box appeared in the center of the screen. A series of test stimuli were then presented and the subject responded either "yes", a particular test stimulus was identical to the memorized stimulus, or "no", the test stimulus was different from the memorized stimulus. "Yes" and "no" responses were recorded by pressing the upper and lower keys with the right middle and index fingers, respectively. The computer recorded reaction time and errors.

In the perceptually loaded condition, a grid of line segments was

placed over the stimulus box in order to hinder the perceptual processing of the dot patterns. The mask had been pretested to insure that no dot pattern's identity was obliterated. The mask only served to prolong the single task reaction times.

In the response loaded condition, subjects were required to press two buttons in succession in order to record a specific response. For a "yes" response, the subject pressed the upper key followed by the lower key. The second key was to be depressed within a time window of .3 seconds to .6 seconds following the first. The desired result was a smooth, coordinated response which produced slightly higher single task reaction times than simply a single key response. Similarly, a "no" response was recorded by first pressing the lower key and then the upper key within the .3 second window. Nonresponses were recorded by the computer when the subject was either too fast (<.3 seconds) or too slow (>.6 seconds) in pressing the second key. The reaction time interval began when the first key was depressed.

Experimental Design

A within subject design was employed where each subject participated in all experimental manipulations. The Sternberg conditions included a baseline condition, a perceptually loaded condition, and a response loaded condition. The failure detection difficulty manipulation varied the cutoff frequency of the random noise function from .32 Hz to .5 Hz. Each of these task manipulations was performed under both single and dual task conditions. All subjects participated in six sessions consisting of two days of practice and four days of data collection. Each session lasted one hour and took place on consecutive days. The cutoff frequency levels were administered on

different days and the particular order was counterbalanced for each subject to avoid the bias of any particular sequence.

Procedure

The practice days were divided into single task and dual task training sessions. All subjects received enough training in the experimental conditions to insure relatively stable performance.

The four experimental days each consisted of fourteen total trials. The failure detection difficulty level remained constant throughout a particular experimental session. During each session, subjects were required to perform two single task failure detection trials, six single task Sternberg trials, and six dual task trials. These Sternberg trials were administered in four alternating blocks of three single task trials followed by three dual task trials. The three Sternberg manipulations consisted of a no mask-single key response condition (baseline), a mask-single key response condition (perceptual loading), and a no mask-double key response condition (response loading). Two replications of each Sternberg manipulation were presented to the subject for both single and dual task conditions. Each trial lasted approximately two minutes and between trials, the subject was given feedback concerning task performance and bonus earned.

Experimenter instructions designated the failure detection task as primary so that subject performance on this task in both single and dual task conditions should be essentially equivalent. Therefore, secondary Sternberg performance should reflect changes in the processing demands of the primary task.

The bonus system reinforced these instructions. The failure detection

bonus depended on hit latency and was halved if one false alarm was generated. Two false alarms resulted in elimination of the failure detection bonus altogether. The Sternberg bonus was contingent on acceptable primary task performance (dual task = single task) and based on reducing reaction time below the previous day's single task reaction time score. Excessive errors also reduced the bonus which could be earned.

RESULTS/DISCUSSION

The summary data for both the failure detection and Sternberg tasks are presented in Table 1. Single and dual task Sternberg performance for both the perceptual and response load conditions are graphically portrayed in Figure 3. Failure detection performance in the .32 Hz and .5 Hz conditions is shown in the top and bottom panels respectively. The experimental results indicate that the interaction between perceptual load and the presence of the failure detection task was statistically significant, $F(2,14) = 8.10$, $p < .01$. Under dual task conditions, a significantly greater increase in Sternberg reaction times was obtained for the mask manipulation compared to the no mask condition. As suggested by the data in Figure 3, no significant positive interaction was found between response load and failure detection. However, an instance of underadditivity was found for the .32 Hz condition, $F(2,14) = 9.81$, $p < .01$. The double key response reaction times were not as severely disrupted under dual task demands as the perceptual load reaction times.

The ability of subjects to maintain consistent primary task performance for both single and dual task conditions is an important requirement for any interpretation of the dual task data. A comparison of the single and dual task failure detection data (see Table 1) revealed essentially equivalent performance for these two conditions, $F(3,21) = 2.17$, $p > .122$. In most cases, subjects were able to maintain superior performance under dual task demands. Thus, we can be relatively secure in the knowledge that similar amounts of processing resources for the failure detection task were used in single as well as dual task conditions. This assumption permits an

Table 1

Mean Task Latencies (seconds)

for Each Processing Load Condition

Load	Condition		
	Baseline	Mask	Double Key
Failure Detection			
Single Task			
.32 Hz	5.594		
.50 Hz	5.201		
Dual Task			
.32 Hz	4.943	5.127	5.220
.50 Hz	5.119	5.094	5.064
Sternberg			
Single Task			
.32 Hz	.617	.687	.667
.50 Hz	.604	.676	.674
Dual Task			
.32 Hz	.784	.914	.794
.50 Hz	.780	.906	.821

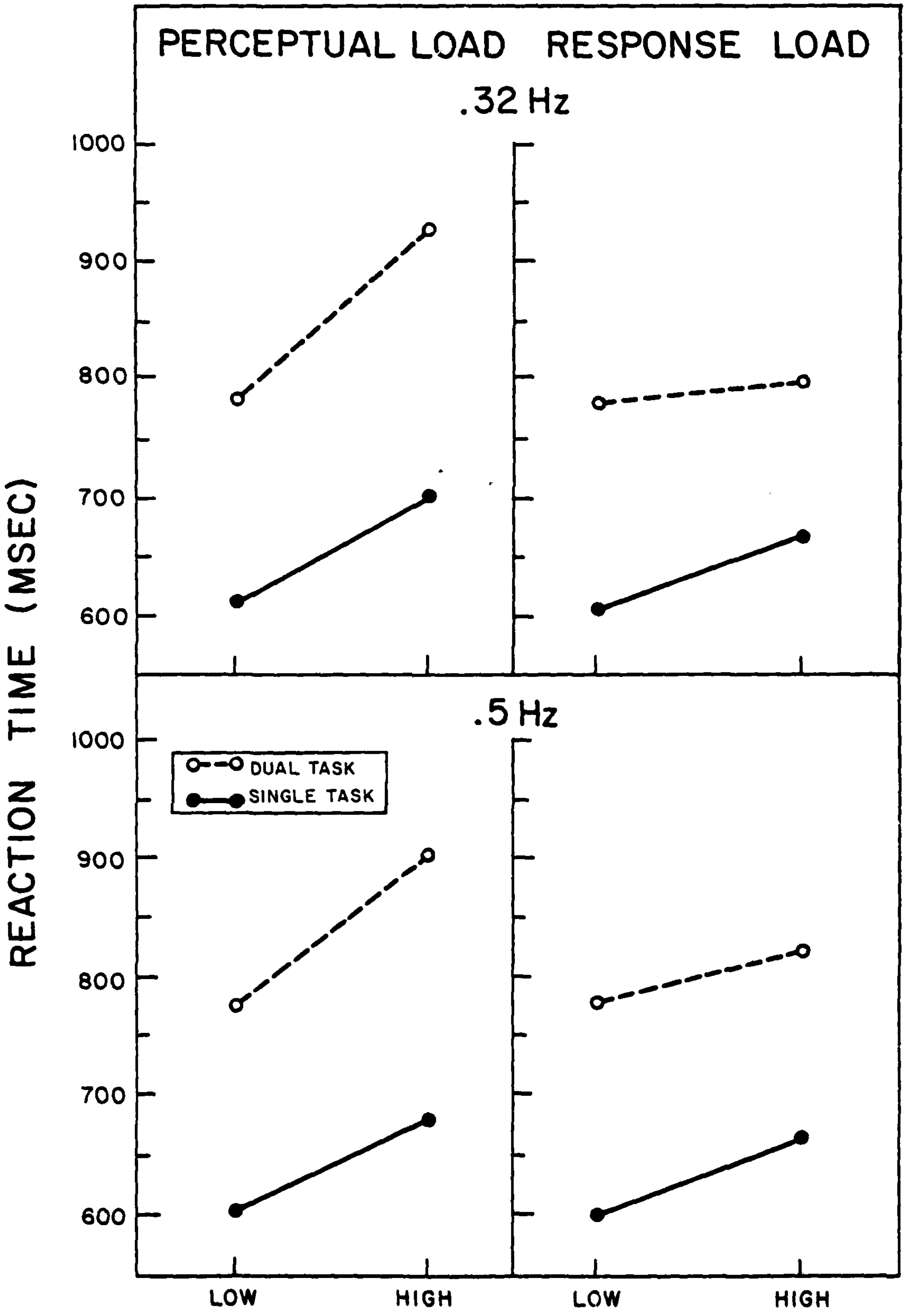

Figure 3. Sternberg dual task decrements.

interpretation of Sternberg reaction time decrements as an indication of task manipulations.

Although maintaining single task failure detection performance under dual task demands is an important requirement for any interpretation of the reaction time data, an equally important consideration is the ability of subjects to avoid utilizing a "resource tradeoff" strategy in producing the observed reaction time decrements. Large variations in dual task failure detection performance across Sternberg conditions may reflect this strategy and could potentially account for the particular pattern of Sternberg data shown in Figure 3. If the higher reaction times in the perceptual load condition are consistently linked with relatively lower failure detection latencies (compared with the response load condition) then a resource tradeoff strategy may have been utilized. Under this interpretation, processing resources are assumed to be diverted (traded off) from the Sternberg task (resulting in higher reaction times) and applied to the failure detection task (resulting in lower hit latencies). As a result, variations in reaction time performance across Sternberg conditions could be explained in terms of subject strategy without reference to competition among hypothesized pools of processing resources.

The presence or absence of such a tradeoff can be illustrated through the use of a performance operating characteristic (POC) (see Figure 4). The efficiency level of the two tasks performed concurrently can be represented within the POC space. Single task performance is indicated by the point of intersection of the POC with the two axes. Dual task performance is identified as a single point within the space representing the decrement score on both tasks relative to their respective single task performance

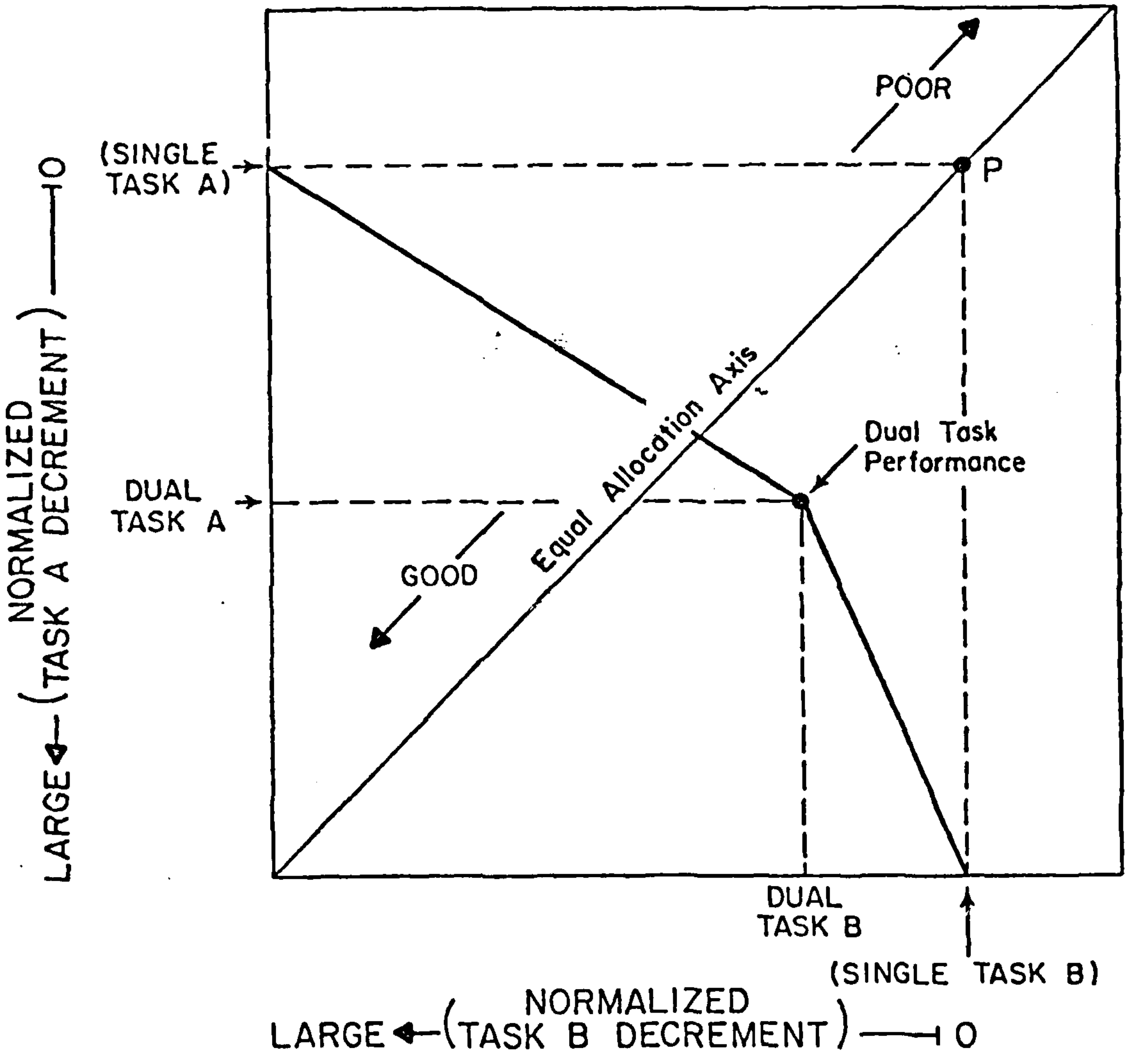

Figure 4. Hypothetical representation of dual task performance within the POC space.

levels. Shifts along the positive diagonal toward the southwest direction represent improvements in time sharing efficiency. Shifts along the negative diagonal represent variations in resource allocation policy.

In order to compare tasks which utilize different dependent variables, the performance measure of each task is converted to a common dimensionless unit such as a normal deviate (Wickens, Mountford, & Schreiner, 1979). In the present study, dual task difference scores for both the reaction time and hit latency measures were divided by the respective mean standard deviations and plotted within the POC spaced for .32 Hz and .5 Hz manipulations (see Figures 5 & 6). A comparison of these dual task difference scores along a common measuring scale reveals a clear separation of respective POCs for the perceptual and response load conditions. The perceptual load condition disrupted dual task efficiency to a much greater extent than in the response load condition.

The results of the analysis of variance support the general impression conveyed by the respective POCs. A comparison of mean dual task failure detection hit latencies across Sternberg conditions reveals no significant variations, $F(2,14) = .234$, $p > .794$. The relatively higher perceptual load reaction times observed under dual task conditions were not necessarily accompanied by correspondingly lower hit latencies. The variation of dual task failure detection performance is not large enough to account for the larger decrements in reaction time performance.

It is also important to insure that the reaction time differences between the perceptual and response load conditions did not result from a speed/accuracy tradeoff. Table 2 contains a summary of the error data for both the failure detection and Sternberg tasks. The results indicate the

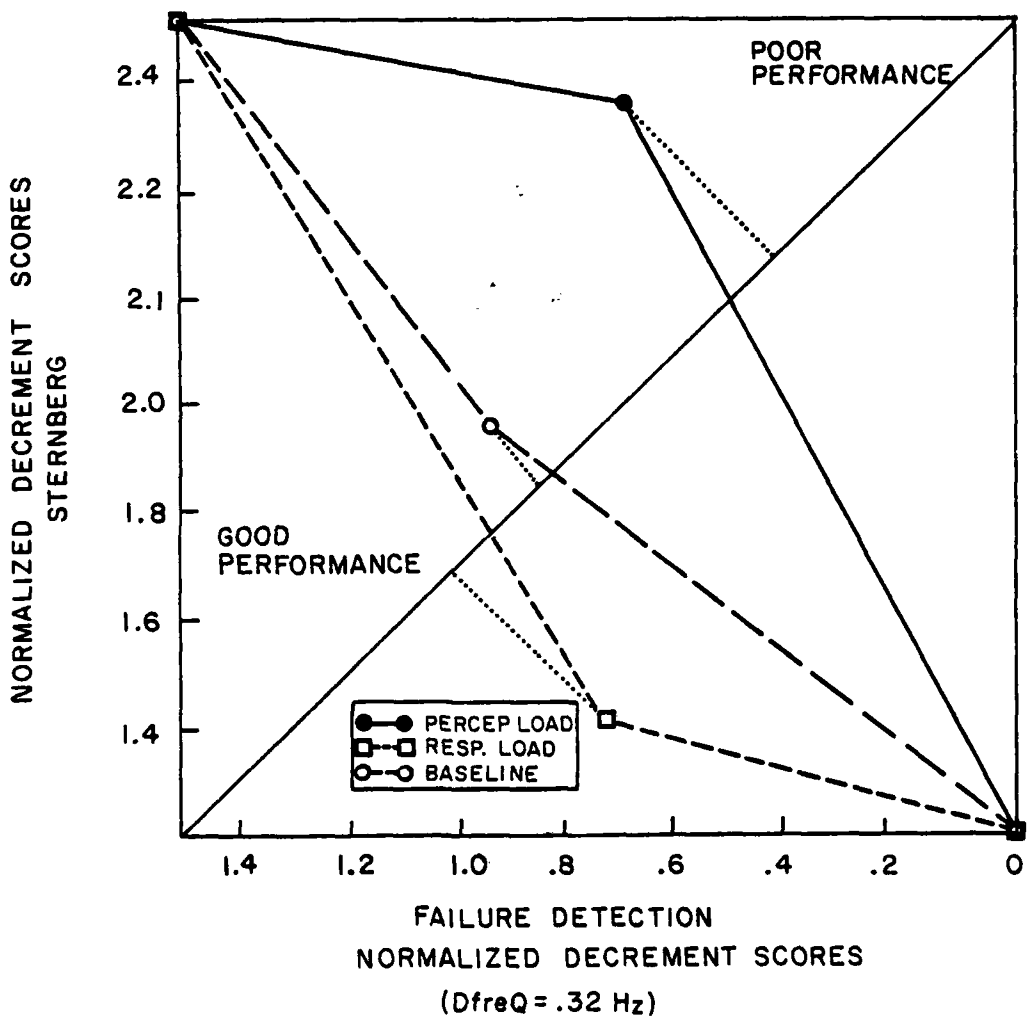

Figure 5. POC representation of dual task performance for the .32 Hz cutoff frequency manipulation.

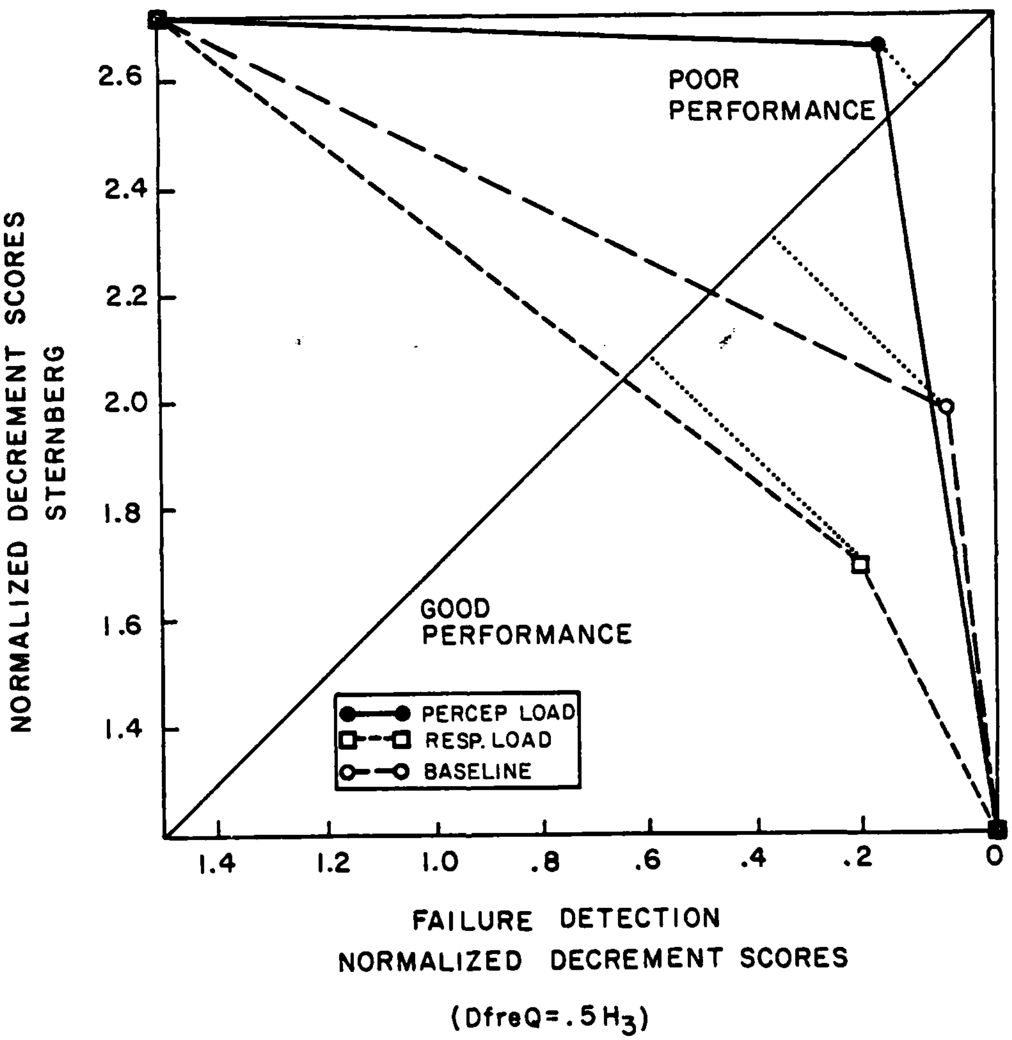

Figure 6. POC representation of dual task performance for the .5 Hz cutoff frequency manipulation.

Table 2

Error Data for the Failure Detection and Sternberg Tasks

	Condition		
Load	Baseline	Mask	Double Key
	False Alarms		
Single Task			
.32 Hz	.063		
.50 Hz	.219		
Dual Task			
.32 Hz	.219	.375	.313
.50 Hz	.656	.219	.281
	Percentage of Sternberg Errors		
Single Task			
	2.33	3.68	5.43
Dual Task			
.32 Hz	2.89	4.33	6.48
.50 Hz	3.20	3.11	6.50

Sternberg errors were significantly greater in the response load condition, $F(2,14) = 6.22$, $p < .05$. However, this error variation could be due to the increased opportunity for error in the double key response condition (recognition errors and double key response errors). In addition, there was no interaction between Sternberg condition and single/dual task demands for reaction time errors. In other words, although the relative percentage of errors varied across Sternberg conditions, this variation was consistent for both single and dual task conditions. A speed/accuracy tradeoff explanation of the results could not be applied to those interpretations of the reaction time data which are concerned with performance variations as a function of Sternberg condition and single/dual task demands.

The effect of the various experimental conditions on the number of false alarms appeared to be generally insignificant, although under dual task demands, there was a significant difference between the cutoff frequency manipulations for the baseline (no mask- single key) Sternberg condition, $F(2,14) = 6.86$, $p < .01$. However, comparisons with corresponding hit latencies does not indicate that this difference was in the direction of a speed/accuracy tradeoff.

These experimental results provide at least some support for the main hypotheses advanced in the beginning of this paper. First, the significant interaction between perceptual load and failure detection demands indicates some degree of processing resource overlap between these two tasks within the framework of the additive factors method. Second, the lack of a significant interaction between response load and failure detection demands provides evidence for the notion of a separation of the respective processing resource pools. The underadditivity observed in the .32 Hz

condition may be attributed to an increased mobilization of response related processing capacity at higher levels of workload which could account for the reduced slope in the dual task condition.

The failure detection task used in this study appears to be primarily perceptually loaded. This conclusion is consistent with previous studies (Wickens & Kessel, 1979b) which investigated the resource demands of failure detection with a different secondary task. In addition, these results also support a stages of processing dimension for the structure specific resource model which is particularly applicable to workload investigations. The general Sternberg paradigm utilized in this study has shown promise as a technique for probing the multidimensionality of workload demands within the context of dual task methodology.

Comparisons of the dual task data obtained for the .32 Hz and .5 Hz cutoff frequency manipulations must be accompanied by cautious interpertation of the experimental results. One aspect of the data which is not immediately interpretable within a resource competition model concerns the difference between single and dual task failure detection hit latency for the two cutoff frequency manipulations. The average single task failure detection hit latency for the .32 Hz manipulation was considerably higher than either its dual task value or the single or dual task latencies for the .5 Hz condition (see Figure 7). This result suggests that dual task requirements actually increased failure detection performance in the .32 Hz condition. This might be explained in terms of relative arousal levels. The slower dynamics of the .32 Hz system may have induced a lower level of arousal which contributed to the consistently higher single task hit latencies in this condition. However, under dual task conditions, the level

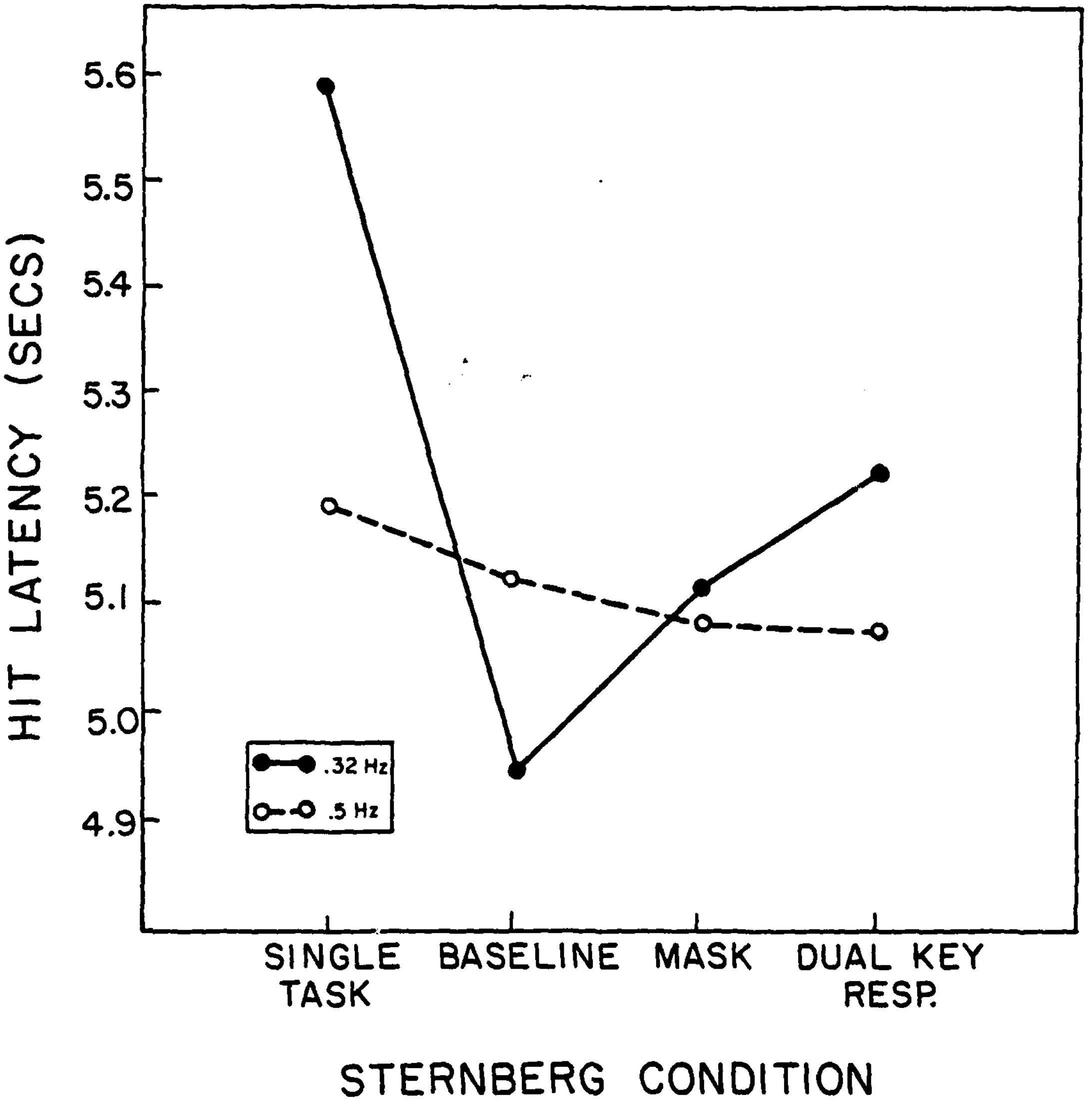

Figure 7. Single & dual task failure detection hit latencies for the .32 Hz & .5 Hz cutoff frequency manipulations.

of arousal increased in the .32 Hz condition to a level more comparable to the .5 Hz condition, and the performance in each condition was considerably more equivalent. Interpretations of the cutoff frequency manipulation as a manipulation of task difficulty are not clearly supported by the data even though, a priori, the increased velocity component in the .5 Hz condition would seem to render this task subjectively more difficult.

The average dual task Sternberg data did not vary significantly between the two cutoff frequency manipulations with the exception of the response load condition. The lower response load reaction time in the .32 Hz manipulation was primarily responsible for the significant interaction between the Sternberg conditions and the cutoff frequency manipulations for dual task reaction time, ($F(2,14) = 4.20$, $p < .05$. It is not clear whether this difference in response load reaction time is an independent effect or whether it can be explained in terms of relative arousal levels.

Perhaps the most important contribution of this study has been to provide evidence for the utility of the general Sternberg paradigm in assessing the locus of processing resource demands for a particular primary task. This procedure is especially appropriate for probing the multidimensional aspects of the generalized workload concept. Workload assessment continues to be an important activity in the human factors evaluation of complex system interactions. Although criticisms of the additive factors method (Pachella, 1974) and alternate conceptions of the structure of the reaction time interval (McClellan, 1978) may weaken the theoretical basis for the Sternberg methodology, this method may still provide some degree of practical application in localizing the workload effects involved in man/machine systems.

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